

Absorption mechanisms in photon induced two-body knockout

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Abstract

Calculations have been performed for the $^{16}\text{O}(\gamma,\text{pn})$ and the $^{16}\text{O}(\gamma,\text{pp})$ reaction in the photon-energy range $E_\gamma = 60\text{-}300 \text{ MeV}$. Besides the contribution from the more common photoabsorption on the pionic degrees of freedom, we have investigated the influence of heavier meson exchange (ρ, σ, ω) and intermediate Δ creation with π and ρ exchange. Whereas the π meson is found to set the main trends, the ρ meson is found not to be discardable in a theoretical description of the (γ,pn) reaction. The incorporation of an energy dependence and a decay width in the Δ propagator is observed to be essential in order to arrive at a more realistic description of (γ,NN) reactions at higher photon energies.

1 Introduction

Photo-induced two-nucleon emission reactions are generally considered as a valuable tool for the investigation of the two-body aspects of nuclear structure [1, 2]. Since the early eighties the major contribution to the (γ,pn) strength is supposed to come from π -meson exchange currents (π -MEC) [3, 4, 5, 6]. As these currents involve charge exchange they do not contribute to the (γ,pp) reaction. In a direct knockout reaction mechanism after photoabsorption on a two-body nuclear current, the (γ,pp) channel can be fed through intermediate $\Delta(1232)$ isobar creation and through heavier meson exchange. In addition to this, the short range correlations (SRC) were suggested [7] to contribute considerably into this channel. The pn channel being considerably stronger, rescattering into the pp channel could

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be expected to give important contributions to (γ, pp) an effect which still needs to be investigated. Continuous efforts to improve on the experimental facilities have resulted in a renewed interest in the field of photon induced two-nucleon emission processes. In the near future, high-resolution (γ, pn) and (γ, pp) data can be expected from Lund, Mainz and Saskatchewan. The progress made in the construction of detection systems should also make the measurement of angular (γ, NN) cross sections feasible in the next coming years [8]. These developments have prompted us to study the physics of the photoabsorption mechanism in (γ, pn) and (γ, pp) reactions in more detail. At this stage all theoretical studies have employed pionic degrees of freedom only. In this work we will extend this approach and in addition to the pion, we will study the influence of heavier meson (ρ, σ, ω) exchange on the (γ, NN) cross section. Moreover, we will investigate under which kinematical conditions effects due to heavier meson exchange can best be looked for.

2 The formalism

In this letter we will focus on the different absorption mechanisms playing a role in the two-nucleon knockout processes. In order to explore this topic in the most transparent conditions we will use a model in which the nuclear structure effects are clearly separated from the physics of the photoabsorption. Any model that aims at treating the final state interaction (FSI) between the outgoing particles and the residual nucleus starting from principal grounds is unfactorized in nature. In such a model the physics of the photoabsorption mechanism and the nuclear-structure aspects of the reaction cannot be separated. Therefore we do not include FSI between the outgoing particles and the residual nucleus nor between the outgoing particles themselves. In a previous paper [6] we have shown that the Gottfried approach is a good research tool as it is numerically tractable and gives a fair approximation to the cross section. In the Gottfried approach, the differential cross section factorizes in a dynamical part S_{fi} which reflects the absorption mechanism and in the probability $F_{hh'}(\mathbf{P})$ to find a NN pair in the single-particle orbits h and h' with total momentum \mathbf{P} and zero separation in the target nucleus :

$$\frac{d^5\sigma^{lab}}{d\Omega_a d\Omega_b dp_b} \sim F_{hh'} S_{fi}. \quad (1)$$

In order to calculate S_{fi} , a microscopic model for the two-body nuclear currents is needed. For the calculations presented here, we account for π , ρ , σ and ω meson exchange currents and Δ isobar currents. The meson-nucleon and meson-isobar coupling constants are taken from a one-boson-exchange parameterization of the Bonn potential [9].

The expression of the pionic exchange currents has been derived from the chiral Lagrangian from ref. [10]. For pseudovector πNN coupling, this leads in lowest order to the π seagull current (fig. 1a) and the π in-flight current (fig. 1b). The combined π seagull and π in-flight current satisfy the continuity equation with the one pion exchange potential (OPEP). We used the nonrelativistic reduction of these currents as they can e.g. be found in ref.[11]. Due to their isospin structure, these currents can only contribute to pn emission in a direct knockout model. For the πNN vertex, a monopole form factor with cut-off mass 1200 MeV [9] has been used. The use of hadronic form factors to regularize the πNN vertices at short internucleon distances, makes the introduction of additional currents necessary in order to conserve the gauge invariance condition with OPEP [12]. These contributions have been taken into account but were found to be small for the photon energies considered in this paper.

The ρ exchange currents have next to a ρ seagull (fig. 1a) and a ρ in-flight contribution (fig. 1b), also a ρ pair contribution (fig. 1c) in which the intermediate nucleon propagator only contains the antinucleon contribution. To derive these ρ exchange current contributions consistently into order $(1/M^2)$ (with M the nucleon mass), it is necessary to start with a relativistic description of the ρNN vertex [9]. The ρ exchange diagrams are then calculated fully relativistically. The nonrelativistic reduction (keep all terms to order $(1/M^2)$) of this expression yields the ρ exchange currents which were used in this paper. It was checked that their expressions agree with the ones given in ref. [13]. A systematic discussion of the influence of the various ρ exchange current contributions as function of the photon energy will be given in a forthcoming paper. In this paper we will study the importance of the total ρ exchange current as compared to the π exchange current. For the ρNN vertex, we also use a monopole hadronic form factor with a cut-off mass 1500 MeV.

Being neutral mesons, the σ and ω mesons can only contribute to the current through the pair diagram (fig. 1c). The expression for the σ and ω exchange currents is obtained along the same lines as described for the ρ meson.

In deriving the current related to intermediate Δ excitation we included both

pion and rho exchange (fig. 1d) and adopted a nonrelativistic approach. This means that $\pi N\Delta$, $\rho N\Delta$ and $\gamma N\Delta$ vertices are obtained from πNN , ρNN and γNN vertices by replacing spin and isospin operators by the corresponding transition operators. In the energy denominator which describes the nonrelativistic delta propagation, the (photon) energy dependence is retained. To account for the finite lifetime of the delta, an energy dependent width is introduced which satisfies unitarity [14] in the πN channel. The hadronic form factors at the $\pi N\Delta$ and $\rho N\Delta$ vertices are taken to be the ones at the πNN and ρNN vertices. The Δ currents with rho exchange are noticed to contain as a subset the terms of the Δ current with pion exchange but with opposite sign. Because of the strong ρNN coupling compared to the πNN coupling a strong destructive interference between both contributions could be expected.

3 Results

All forthcoming cross sections were obtained for the $^{16}\text{O}(\gamma, \text{NN})$ reaction in planar kinematics (i.e. the two emitted nucleons and the photon remain in the same fixed plane), except when stated explicitly. The cross sections involve two nucleon emission from all occupied sp orbits, where the hole states are described with harmonic oscillator wave functions.

To start with we concentrate on the (γ, pn) reaction. In fig. 2 we displayed the contribution from the different absorption mechanisms to the integrated $^{16}\text{O}(\gamma, \text{pn})$ cross section as a function of the photon energy. We have calculated the contribution arising from the two low mass isovector mesons (π and ρ) which give rise to the electromagnetic exchange operators through the seagull and the in-flight diagrams (fig. 1a-b) and also through the pair diagram (fig. 1c) for the ρ meson. The exchange current contributions from the two isoscalar mesons (σ and ω) were found to be small, because they only contribute through the pair diagram (fig. 1c) which is of relativistic origin. Even at low photon energies the interference between π and ρ meson exchange reveals an appreciable reduction of the cross section (fig. 2), indicating the importance to incorporate ρ meson exchange in the reaction process.

It is tempting to simulate the reducing effect of the ρ meson on the total strength, by using an effective cut-off parameter in the hadronic form factors. It is apparent from fig. 2 that the reducing effect on the total (γ, pn) cross sections due to heavier meson exchange can be accomplished in a calculation with only

pionic degrees of freedom, provided that an effective cut-off parameter of 800 MeV (dot-dashed curve) is adopted.

We have investigated the usefulness of this effective approach with a modified cut-off parameter in more detail. To this end, we plotted in fig. 3a the fivefold differential cross section ($d^5\sigma^{lab}/d\Omega_p d\Omega_n dp_p$) at $E_\gamma=100$ MeV and $T_p=40$ MeV. In order to make the discussion more transparent only π currents have been included. The proton and neutron angles are determined relative to the direction of the photon momentum. Immediately, we remark the dominance of back-to-back emission in the two-nucleon emission process. The driving mechanism in this back-to-back dominance is the missing momentum $\mathbf{P} = \mathbf{p}_a + \mathbf{p}_b - \mathbf{q}_\gamma$, with \mathbf{p}_a (\mathbf{p}_b) the momentum of the first (second) outgoing particle and \mathbf{q}_γ the photon momentum [1]. The missing momentum dependence reflects itself in the nuclear structure factor $F_{hh'}(\mathbf{P})$. This is illustrated in fig. 3b where we plotted $F_{hh'}(\mathbf{P})$ for the same kinematical conditions as in fig. 3a. It is obvious that the general structure of the angular cross sections is a mere reflection of the $F(\mathbf{P})$ dependency. With the eye on future comparisons with the data, the differential cross sections can best be studied under kinematical conditions which maximize the strength. For that purpose we have investigated angular cross sections as a function of the outgoing proton angle in which the corresponding neutron angle is obtained through maximizing $F_{hh'}(\mathbf{P})$. This procedure corresponds with exploring the ridge of the angular cross sections of the type displayed in fig. 3a. By doing this the missing momentum \mathbf{P} can be more or less kept constant over the covered proton angle range and the large functional dependence of the angular cross section on the function $F(\mathbf{P})$ can be ruled out. Therefore, calculations performed along these lines are most sensitive to the dynamics of the photoabsorption mechanism which is contained in the factor S_{fi} . We have adopted this approach to look for measurable signs of ρ absorption in the angular cross sections. In fig. 4 we show the calculated angular cross $^{16}\text{O}(\gamma, \text{pn})$ cross section at two different values of the photon energy ($E_\gamma = 70$ and 140 MeV). These cross sections have been obtained through the maximizing procedure explained earlier. We have displayed the angular cross sections for the π and $\pi + \rho$ absorption diagrams. In the calculation which involves both the π and the ρ components the cut-off parameters of the Bonn potential have been used. On the other hand, the cross section including only the π absorption diagrams has been obtained with the effective cut-off parameter (i.e. $\Lambda_\pi = 800$ MeV instead of 1200 MeV). It was observed before that a reduction of the cut-off parameter would simulate rather

well the interference effect taking place when including ρ meson exchange in the reaction process, at least for the total integrated cross section. This “effective” procedure is obviously less satisfactory in the reproduction of the angular cross sections. At low photon energies ($E_\gamma = 70$ MeV) an almost similar behaviour of both approaches is observed. This similarity disappears with increasing photon energies. From fig. 4 it is clear that as the ρ meson absorption gains in importance, the angular cross section evolves to an almost flat course, an effect which cannot be reached when only pionic degrees are accounted for. This effect will be even more pronounced at higher photon energies. We conclude that although the “effective” approach is satisfactory for the integrated (γ, pn) cross section, it loses its usefulness once we turn to angular cross sections at higher photon energies. As such a systematic study of the angular cross section at a fixed value of the missing momentum P , seems to be a better tool than the integrated cross section to understand the underlying physics of the (γ, NN) reactions. Experimental efforts to actually measure the angular cross sections are in progress [8].

As could be expected, with increasing photon energies the Δ isobar components gain in importance. This has been illustrated in fig. 5a in which we compare the mesonic $(\pi + \rho)$ contribution to the (γ, pn) cross section with the full calculation, which apart from the π and the ρ has a $\Delta(1232)$ part. As has been explained in section 2, we adopt an energy dependent nonrelativistic Δ propagator and account for a decay width. For photon energies exceeding 150 MeV, the Δ current is the dominant contribution to the (γ, pn) cross section. In fig. 5 we have also plotted the results obtained in the commonly adopted static Δ approximation (neglecting the energy dependence and the decay width in the Δ propagator). It is clear that for pn emission the static Δ approximation is not able to reproduce the Δ resonance peak and gives rise to results that differ quite drastically from the energy dependent results. Surprisingly, this seems to be even the case at relatively low photon energies.

Let us now turn to the (γ, pp) reaction. In a direct knockout model, we expect the Δ current to dominate the (γ, pp) cross section as the major meson exchange currents only contribute when a photon gets absorbed by a proton-neutron pair. We have found that the mere influence of the mesonic currents, which is restricted to ρ , σ and ω absorption through the pair diagram (fig. 1c), on the pp cross sections is a slightly modifying effect at photon energies below 100 MeV where the Δ component results in very small cross section. In this energy range the (γ, pp) cross section is negligible in comparison with the (γ, pn)

contribution. In fig. 5b we display the Δ contribution to the pp channel for the two types of Δ propagators discussed above. Unlike the proton-neutron emission reaction, the two proton emission reaction is rather well described by the static Δ propagator for photon energies below 180 MeV. This different behaviour in the (γ, pn) and the (γ, pp) channel can be attributed to the destructive interference between the direct and the exchange matrix elements.

In order to get some handle on the realistic character of our calculations, we have calculated the contribution of the (γ, pn) and the (γ, pp) to the total photoabsorption strength in ^{16}O . This procedure involves, apart from the sum over all occupied single-particle states, an integration over the solid angles and the kinetic energies of both escaping particles. In the peak of the $\Delta(1232)$, the (γ, pn) contribution to the total photoabsorption strength is predicted to be 2.40 mb. The total photoabsorption cross section in the Δ peak is measured to be about 7 mb for ^{16}O [15]. The major contribution of this strength will go into π decay of the Δ . In this sense, the predicted 2.40 mb appears like an overestimation. It has to be kept in mind that our results have been obtained in the factorized Gottfried approach which does not involve any type of FSI. The latter is known to yield a reduction of the cross section [7, 16]. On top of that, in a previous work we have shown that the Gottfried approximation will generally lead to an overestimation of the full unfactorized cross section [6]. In passing it is worth mentioning that we predict a value of 5.26 mb for the contribution of the pn channel to the Δ photoabsorption peak when we discard the ρ contribution to the Δ diagrams of fig. 1(d). This should be considered as a totally unrealistic value. Inclusion of ρ degrees of freedom in the construction of the Δ currents turns out to be indispensable in order to arrive at a realistic description of the expected strength in the (γ, pn) channel.

It was already noted by Riska [17] - in calculations with a static Δ current - that the main effect of the Δ current with ρ exchange is to strongly reduce the effect of the Δ current with π exchange. We confirm here - for a Δ current with an energy-dependent Δ propagator - the importance of retaining both π and ρ contributions.

4 Summary

We have investigated the π , ρ , σ , ω and Δ contributions to the (γ, NN) cross section at intermediate energies. In order to keep the physics of the photoab-

sorption separate from the nuclear-structure effects we have used the factorized Gottfried approach. The σ and ω meson were checked not to give any appreciable contribution to the cross sections. On the other hand, the π - ρ interference term yields a considerable reduction of the leading π exchange current contribution. We have shown that the influence of ρ meson absorption on the total cross section can be simulated quite well in a calculation which involves only π degrees of freedom when introducing an effective cut-off mass of 800 MeV in the hadronic π NN form factor. This statement, however, does no longer hold for the angular cross sections at a fixed value of the missing momentum P , in which the effect of ρ absorption is clearly reflected in the shape and where it is consequently important to include both π and ρ meson degrees of freedom. This points towards a selective type of angular cross sections being a better research tool than integrated (γ, NN) strength distributions to pin down the physics of photon induced two-nucleon emission processes. We have also assessed the role of the Δ current which has been observed to dominate the MEC once the photon energy exceeds 150 MeV. It was found important to retain both the pion and rho contributions to the Δ current because of the strong destructive interference between them. Including solely the π decay of the Δ isobar leads to a severe overestimation of the strength in the resonance region. The static approach of the Δ current seems only to be reasonable for the (γ, pp) reaction and this up to photon energies of 180 MeV. Summarizing, we have observed a general sensitivity of the calculated (γ, NN) cross sections to effects related to ρ degrees of freedom. Accordingly, extensive (γ, NN) measurements might help elucidate the short-range features of the NN interaction.

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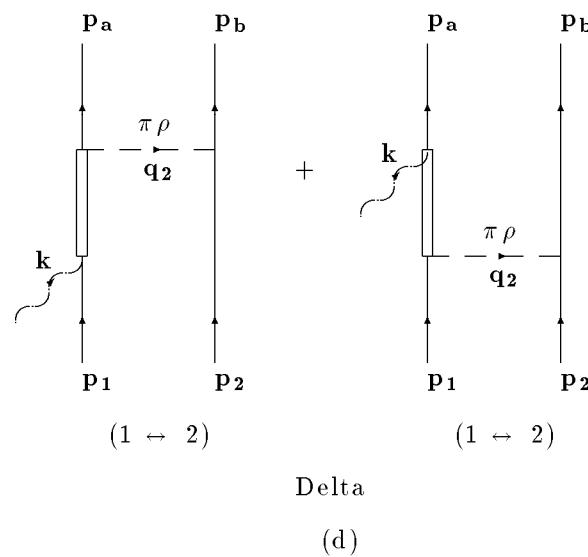
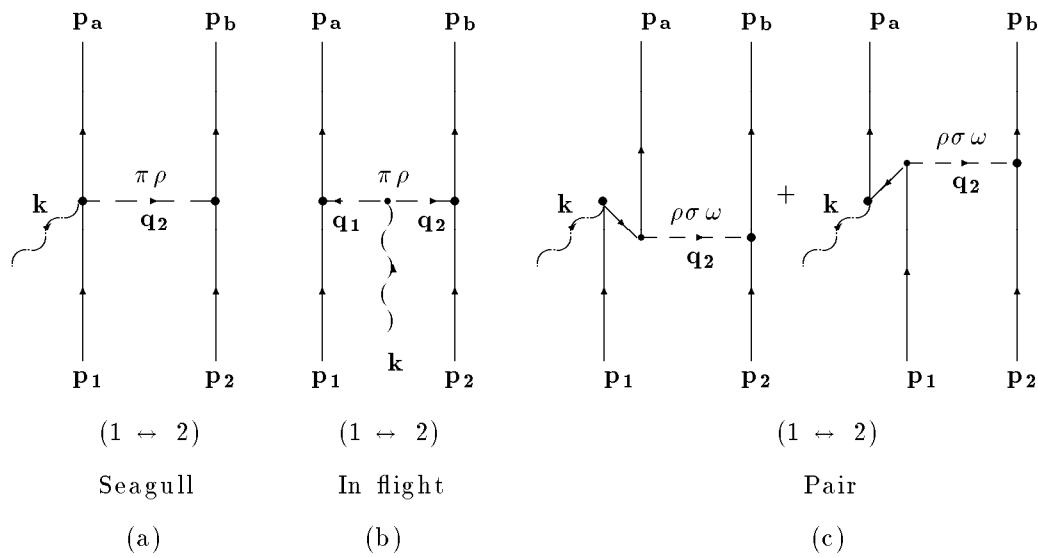
Figure 1: The Feynman diagrams used to calculate the nuclear current operator. Diagrams (a-c) correspond to the MEC and diagram (d) to the Δ isobar.

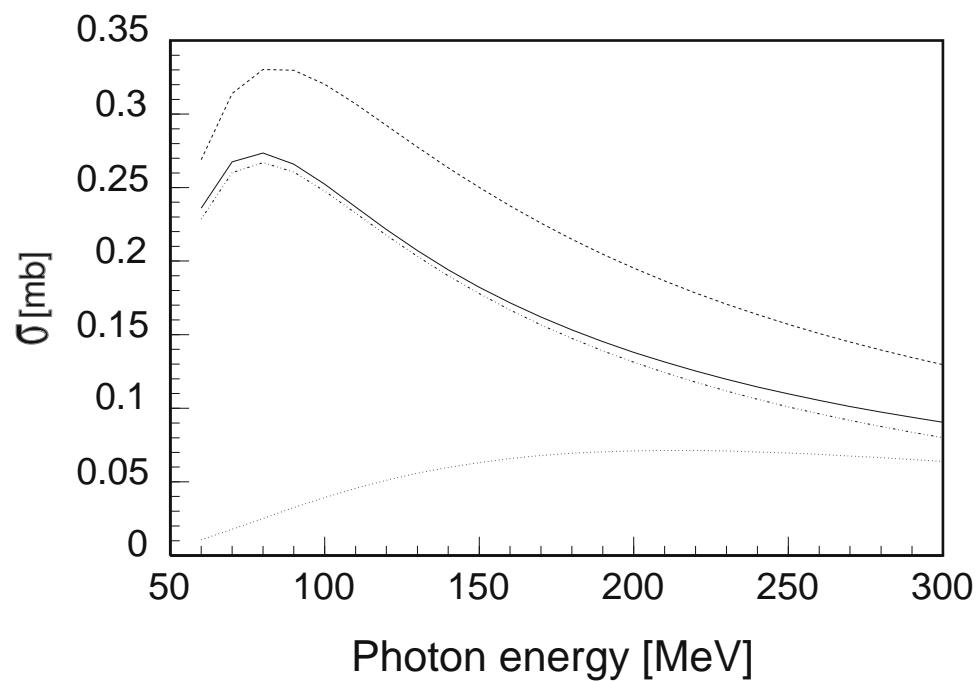
Figure 2: Different mesonic absorption mechanisms contributing to the $^{16}\text{O}(\gamma, \text{pn})$ cross section in planar kinematics as a function of the photon energy. The contributions from the π -MEC (dashed curve- $\Lambda_\pi = 1200$ MeV), ρ -MEC (dotted curve- $\Lambda_\rho = 1500$ MeV) and $\pi\rho$ -MEC (full curve- $\Lambda_\pi = 1200$ MeV, $\Lambda_\rho = 1500$ MeV) are shown. Also shown is the π -MEC contribution with $\Lambda_\pi = 800$ MeV (dot-dashed curve).

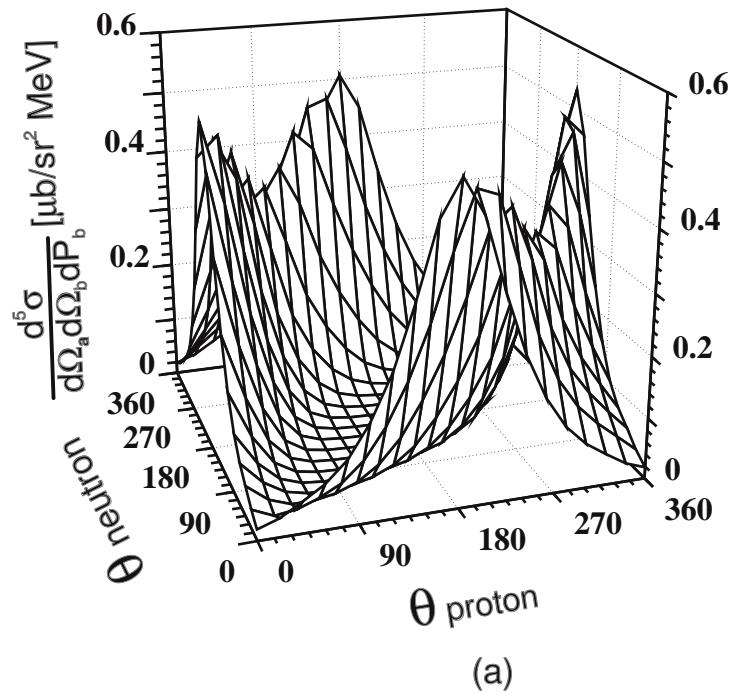
Figure 3: (a) Differential cross section ($d^5\sigma^{lab}/d\Omega_p d\Omega_n dp_p$) for the $^{16}\text{O}(\gamma, \text{pn})$ reaction at $E_\gamma = 100$ MeV and $T_p = 40$ MeV. Only pionic absorption mechanisms are accounted for. (b) The function $F(\vec{P} = \vec{p}_p + \vec{p}_n - \vec{q}_\gamma)$ for the kinematical conditions of (a).

Figure 4: The contributions to the cross section in the kinematics as explained in the text. for $\pi\rho$ -MEC and the effective π -MEC at different photon energies in function of the proton angle. At $E_\gamma = 70$ MeV we plotted the $\pi\rho$ -MEC (full curve) and effective π -MEC (dotted) contribution. Idem dito at $E_\gamma = 140$ MeV (dashed) (dot-dashed).

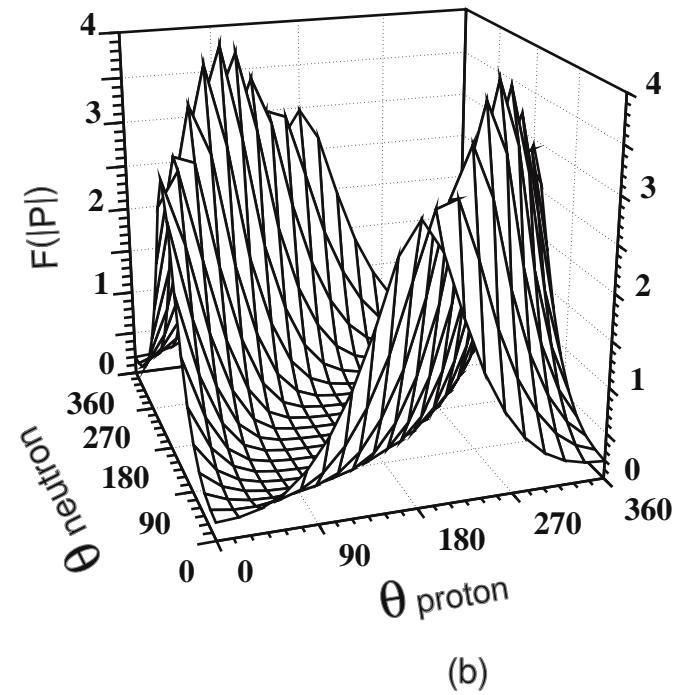
Figure 5: The $^{16}\text{O}(\gamma, \text{NN})$ cross section as function of the photon energy for different mesonic and isobaric absorption mechanisms. (a) pn emission : $\pi\rho$ -MEC contribution (dashed curve) and MEC- Δ contribution as calculated with an energy-dependent propagator (solid curve) and in the static limit (dotted curve). (b) pp emission : curves as in (a).



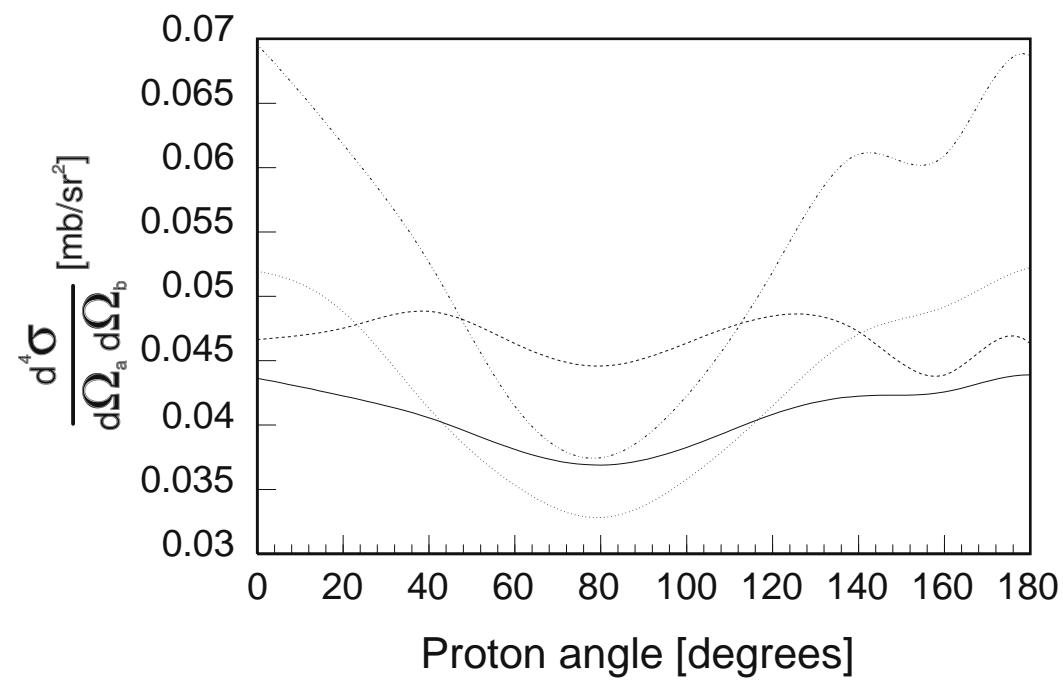


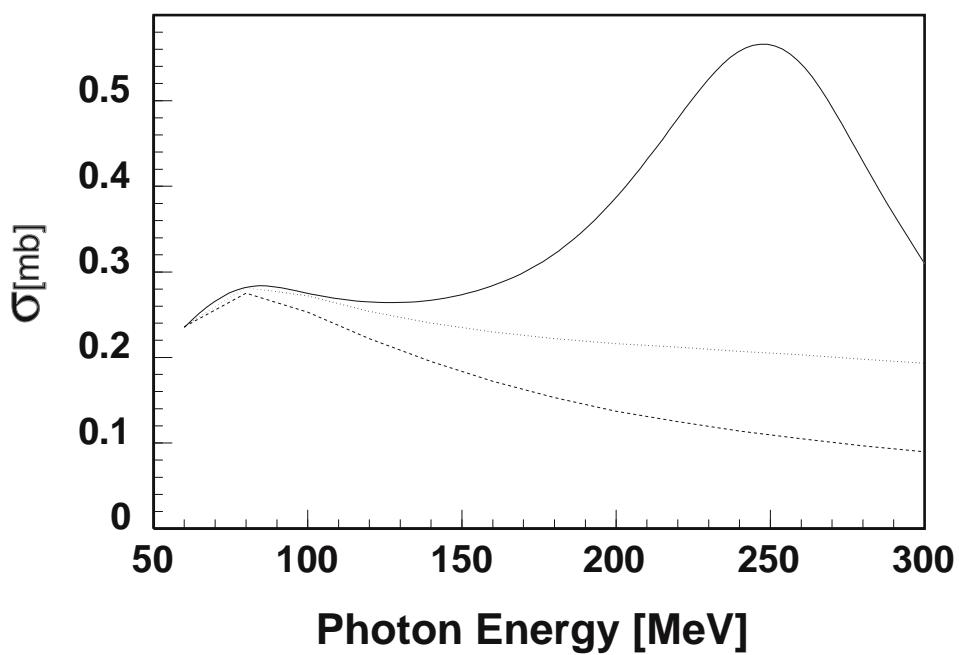


(a)

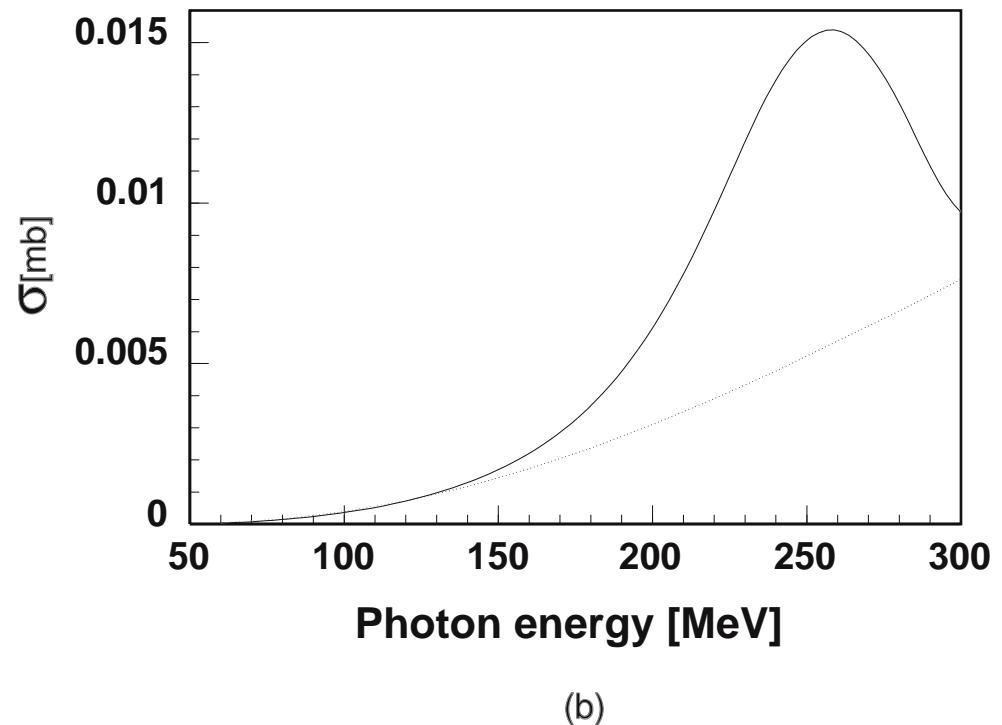


(b)





(a)



(b)